Impact of tau polarization on the study of the MSSM charged Higgs bosons in top quark decays at the ILC

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The process of top quark pair production at the ILC with subsequent decays of one of the top quarks to a charged Higgs boson and b-quark is considered. The charged Higgs decays to tau leptons whose polarization is the opposite to those coming from W bosons. This difference is reflected in the energy distributions of the tau decay products in the top quark rest frame, which can be reconstructed at the ILC using the recoil mass technique. We present an analysis including spin correlations, backgrounds, ISR/FSR and beamstrahlung, and show that a fit of the shape of the pion energy spectrum yields the charged Higgs boson mass with an accuracy of about 1 GeV.

1. CHARGED HIGGS AND TAU POLARIZATION

The mechanism of spontaneous electroweak symmetry breaking in the MSSM leads to a Higgs sector with five physical states: two CP-even Higgs bosons, h and H, one CP-odd one, A, and two charged Higgs bosons $H^{\pm}$ (If CP is violated then the three neutral Higgs bosons will not have definite CP-parity.). The discovery of the charged Higgs bosons would be very important, as it would show directly that the Higgs sector has more complicated structure than the one in the Standard Model, thus providing clear evidence for physics beyond the SM.

The charged Higgs boson couples strongly to the fermions of the third generation. If the charged Higgs is heavy $(M_{H^{\pm}} > M_t)$, it can easily be detected in decays to top and bottom quarks $(H^- \to \bar{t}b)$ by examining the $\bar{t}b$ invariant mass spectrum. In this case, $M_{H^{\pm}}$ may be measured to, at best, about 5 GeV at the LHC [1], and about 1 GeV at an e^+e^- linear collider running at an energy of 800 GeV and collecting a luminosity of 500 fb^{-1} [2]. In a number of other scenarios, however, the charged Higgs bosons will be rather light $(M_{H^{\pm}} < M_t)$. A precise measurement of $M_{H^{\pm}}$ in that range is a challenging task for any collider. In this case the charged Higgs decays dominantly to a tau lepton and neutrino $(H^{\pm} \to \tau^{\pm}\nu)$, and it is impossible to reconstruct directly the invariant mass of the di-tau final state. However, due to the polarization of the $\tau^{\pm}$ leptons, the energy of the $\tau^{\pm}$ decay products depends strongly on $M_{H^{\pm}}$, a feature that can be exploited to extract $M_{H^{\pm}}$ indirectly. The main background to a $H^{\pm}$ signal in the $\tau^{\pm}$ decay mode comes from the W-boson decays $W^{\pm} \to \tau^{\pm}\nu$. However, thanks to the different structure of the $H^{\pm}$ and $W^{\pm}$ electroweak interactions to $\tau^{\pm}$-leptons, the tau polarization is very different which will allow a separation of $H^{\pm} \to \tau^{\pm}\nu$ and $W^{\pm} \to \tau^{\pm}\nu$ on a statistical basis. More specifically, the $\tau^{\pm}$ decay products $(\tau^+ \to \pi^+\bar{\nu}$, or $\tau^+ \to \rho^+\bar{\nu}$, etc.) have strikingly different topologies according as to whether they originate from a parent $W^{\pm}$ or $H^{\pm}$. The importance of tau polarization in searches for charged Higgs bosons has already been stressed in previous studies [3].

The key point is that τ^- leptons arising from $H^- \to \tau^-\nu$ decays are almost purely right-handed, in contrast to the left-handed τ^- leptons which arise from W^- decays. This contrast follows from the helicity flip nature of the Yukawa couplings of the Higgs fields, and the helicity conserving nature of the gauge interactions. The most dramatic
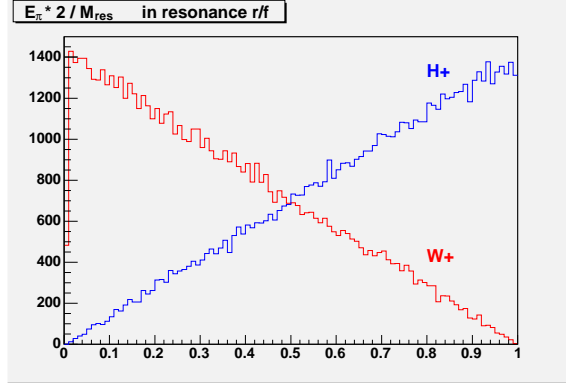
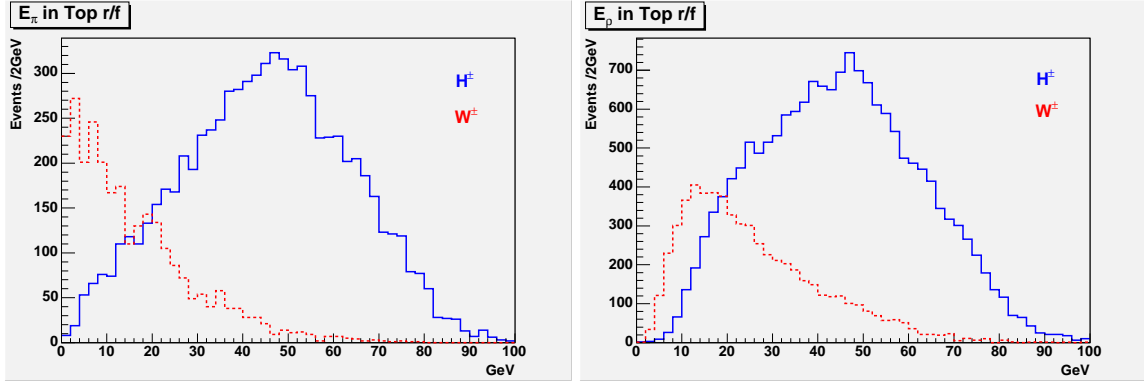Figure 1: $\pi^{\pm}$ meson energy spectrum in the resonance rest frame.

Figure 2: The energy spectrum of the $\pi^{\pm}$ meson (left) and $\rho^{\pm}$ meson (right). The dotted line corresponds to the background, and the solid one to signal.

difference is seen in the energy distribution for the single pion channel ($H^+/W^+ \to \tau^+\nu \to \pi^+\nu\bar{\nu}$) in the rest frame of the parent boson ($W^{\pm}$ or $H^{\pm}$) – see Fig. 1.

In practice, it is nearly impossible to reconstruct the rest frame of the W^+ or H^+ bosons because the momentum of the neutrinos cannot be measured. Instead, one can use the top quark pair production channel with top quark decays ($t \to H^+b$) and reconstruct the top quark rest frame. This is possible at a linear collider when the second produced top quark decays hadronicly, in which case one uses the recoil mass technique analogous to those in Higgs boson studies [2, 4].

The distributions for the energy of the single pion in the top rest frame has the following form [5] for $H^{\pm}$ and $W^{\pm}$ cases, respectively.

$$\frac{1}{\Gamma}\frac{d\Gamma}{dy_\pi} = \frac{1}{x_{max} - x_{min}} \begin{cases} (1-P_\tau)log\frac{x_{max}}{x_{min}} + 2P_\tau y_\pi (\frac{1}{x_{min}} - \frac{1}{x_{max}}), & 0 < y_\pi < x_{min} \\ (1-P_\tau)log\frac{x_{max}}{y_\pi} + 2P_\tau(1 - \frac{y_\pi}{x_{max}}), & x_{min} < y_\pi \end{cases} \quad (1)$$

where $y_\pi = \frac{2E_\pi^{top}}{M_{top}}$, $x_{min} = \frac{2E_\tau^{min}}{M_{top}}$, $x_{max} = \frac{2E_\tau^{max}}{M_{top}}$, $E_\tau^{min} = \frac{M_R^2}{2M_{top}}$, $E_\tau^{max} = \frac{M_{top}}{2}$. For the W boson, $P_\tau = -1$, and for the charged Higgs boson, $P_\tau = 1$. [1]

The energy distribution for a pion from $H^{\pm}$ decay has a maximum at the point $E(\pi^{\pm}) = M_{H^{\pm}}^2/(2M_t)$, as shown in Fig. 2 (left). This dependence allows one to extract $M_{H^{\pm}}$ from the shape of the spectrum. One can also take into

[1]For simplicity, in Eq. 1 we have neglected the b-quark and tau-lepton masses, while these masses have been included in all numerical simulations.

account $\rho^{\pm}$ decay channel ($\tau^+ \rightarrow \rho^+ \nu$), which has twice the branching ratio as the pion channel. The shape of the $\rho^{\pm}$ energy distribution is more complicated, however, and is less sensitive to $M_{H^{\pm}}$, as shown in Fig. 2 (right). More detailed studies are needed for this channel.

2. EFFECTIVE $\bar{t}bH^{\pm}$ INTERACTION IN THE MSSM

For our simulations described in the next section, we use the effective Lagrangian approach for the MSSM presented in Ref. [6]. The effective Lagrangian of charged Higgs interaction with fermions of the third generation has the form:

$$L \simeq \frac{g}{\sqrt{2}M_W} \frac{\bar{m}_b(Q)\tan\beta}{1+\Delta m_b}[V_{tb}H^+\bar{t}_L b_R(Q) + h.c.], \tag{2}$$

where $\bar{m}_b$ is the running bottom mass in the $\overline{\text{MS}}$ scheme. The width of the top quark decay to a charged Higgs and b-quark takes the form:

$$\Gamma_{MSSM}(t \rightarrow bH^+) \simeq \frac{\Gamma_{QCD}^{imp}(t \rightarrow bH^+)}{(1+\Delta m_b)^2} \tag{3}$$

where

$$\Delta m_b = \frac{\Delta h_b}{h_b}\tan\beta \sim \frac{2\alpha_S}{3\pi}\frac{\mu M_{\tilde{g}}}{max(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, M_{\tilde{g}}^2)}\tan\beta + \Delta_b^{\tilde{t}\tilde{\chi}^+} \tag{4}$$

$$\Delta_b^{\tilde{t}\tilde{\chi}^+} \sim \frac{h_t^2}{16\pi^2}\frac{\mu A_t}{max(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)}\tan\beta. \tag{5}$$

The Δm_b correction proceeds from the one-loop vertex corrections, which modify the relation of the bottom Yukawa coupling to the bottom quark mass. Similar corrections are induced in the neutral Higgs sector [7]. The QCD improved top-quark decay width is given by [6],

$$\Gamma_{QCD}^{imp}(t \rightarrow bH^+) = \frac{g^2}{64\pi M_W^2}m_t(1-q_{H^+})^2\bar{m}_b^2(m_t^2)\tan^2\beta \times$$
$$\left\{1 + \frac{\alpha_S(m_t^2)}{\pi}\left[7 - \frac{8\pi^2}{9} - 2\log(1-q_{H^+}) + 2(1-q_{H^+})\right.\right.$$
$$\left.\left. + \left(\frac{4}{9} + \frac{2}{3}\log(1-q_{H^+})\right)(1-q_{H^+})^2\right]\right\} \tag{6}$$

The above expression, Eq. (3), takes into account the dominant supersymmetric corrections to all orders in perturbation theory. It also includes the resummation of the large m_t/m_b and $m_H^{\pm}/m_b$ logarithms, which amounts to replacing m_b by the running bottom mass at the proper scale [6], as well as all finite one-loop QCD corrections.

In the numerical similations, for any given set of supersymmetric particle mass parameters, we have computed the Δm_b corrected charged Higgs Yukawa couplings with fermions of the third generation, by means of the program CPSuperH [8].

3. SIMULATIONS

The numerical simulations have been performed assuming a center of mass energy $\sqrt{s} = 500$ GeV and a total integrated luminosity $\mathcal{L} = 500$ fb^{-1}. We have performed detailed computations and Monte Carlo simulations for three different sets of MSSM parameters, all leading to light charged Higgs bosons. The first two scenarios are based on the mass parameters $M_Q = M_U = M_D = 1$ TeV, $M_{\tilde{g}} = M_2 = 1$ TeV, $A_t = 500$, $\mu = \pm 500$ GeV, and $\tan\beta = 50$, which give $M_{H^{\pm}} = 130$ GeV. The branching ratio $BR(t \rightarrow H^{\pm}b)$ will be enhanced or suppressed depending on the

sign of μ. The third parameter set falls in the so-called "intense-coupling regime" where the neutral Higgs boson masses are close to each other, and they couple strongly to fermions of the third generation [9]. In this case, we have $\mu = 1000$ GeV, $\tan\beta = 30$ and $M_{H^\pm} = 146$ GeV. The branching ratios for these three examples are

$$
\begin{aligned}
&(i)\;\; M_{H^\pm} = 130 \text{ GeV}, && \mu < 0 \text{ and } \tan\beta = 50: && BR(t \to H^+b) = 0.24 \\
&(ii)\;\; M_{H^\pm} = 130 \text{ GeV}, && \mu > 0 \text{ and } \tan\beta = 50: && BR(t \to H^+b) = 0.091 \\
&(iii)\;\; M_{H^\pm} = 146 \text{ GeV}, && \mu > 0 \text{ and } \tan\beta = 30: && BR(t \to H^+b) = 0.063
\end{aligned}
$$

These points are not excluded by Tevatron searches which lead to the bound $BR(t \to H^+b) < 0.42$ at 95% C.L. when $M_{H^\pm} < 150$ GeV [10]. The couplings have been implemented in CompHEP [11], which has been used to compute the cross sections for signal and background processes, including decays of top to $W^\pm$ and $H^\pm$ which subsequently decay to polarized $\tau^\pm$ leptons. CompHEP was also used to generate events, and effects from initial state radiation and Beamstrahlung were included. Polarized $\tau^\pm$ decays have been simulated using TAUOLA [12] interfaced to CompHEP. Hadronization and energy smearing in the final state are accounted for by means of PYTHIA [13] using the CompHEP-PYTHIA [14] interface based on Les Houches Accord [15]. Effects from final state radiation have been implemented using the PHOTOS library [16].

A brief description of our fitting procedure is given here. The fitting function is the sum of two functions, one for signal and one for background. For simplicity and without loss in accuracy we chose the following form for the charged Higgs signal piece, which is motivated by the theoretical spectrum:

$$
H(x) = par_1 k_0(|x - k_1| + k_2 x - k_3), \quad x = E_\pi \tag{7}
$$

where: $k_0 = M_t^3/[par_2^2(par_2^2 - M_t^2)]$, $k_1 = par_2^2/(2M_t)$, $k_2 = 2par_2^2/M_t^2 - 1$, $k_3 = par_2^2/(2M_t)$, with $par_2 = M_{H^\pm}$. There are two free parameters: the parameter par_1 gives the overall normalization of the signal events, and the parameter par_2 is the charged Higgs mass itself. The function $H(x)$ has zeros at the points $E_\pi = 0$ and $E_\pi = M_t/2$, and a maximum at the point $E_\pi = M_{H^\pm}^2/(2M_t)$ as follows from the theoretical spectrum. For the background function we use a forth-order polynomial of the following form:

$$
B(x) = par_3 f(x), \quad x = E_\pi \tag{8}
$$

where $f(x) = c_0 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 x^4$, and the fitting parameter par_3 gives the normalization of the number of the background events. The coefficients $c_0, \ldots, c_4$ are fitted from the shape the background pion energy distribution.

We use the method of maximum likelihood to fit a spectrum created from simulated signal and background events, and obtained the following results for the three cases described above [2]

$$
\begin{aligned}
&(i)\;\; M_{H^\pm} = 129.7 \pm 0.5 \text{ GeV}, \\
&(ii)\;\; M_{H^\pm} = 129.4 \pm 0.9 \text{ GeV}, \\
&(iii)\;\; M_{H^\pm} = 145.5 \pm 0.9 \text{ GeV} .
\end{aligned}
$$

Figure 3 shows results of the simulations and fits.

4. CONCLUDING REMARKS

The tau polarization is a powerful discriminant separating $H^\pm \to \tau^\pm \nu$ from $W^\pm \to \tau^\pm \nu$ in top decays in scenarios with rather light charged Higgs bosons, and with large values of $\tan\beta$, which enhance the $tbH^\pm$ coupling. In this study, we have considered three cases with $M_{H^\pm} \approx 130$ GeV and $\tan\beta = 30$–50. They illustrate how the $tbH^\pm$ coupling can be enhanced or suppressed to the extent that $BR(t \to H^\pm b)$ varies from 6% to 24%. A fit to the

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[2]We are taking into account the expected accuracy, of about 100 MeV, for the top quark mass determination from the top-quark pair threshold scan at the ILC (see Ref. [2]), which adds only a small contribution to the charged Higgs mass uncertainties.
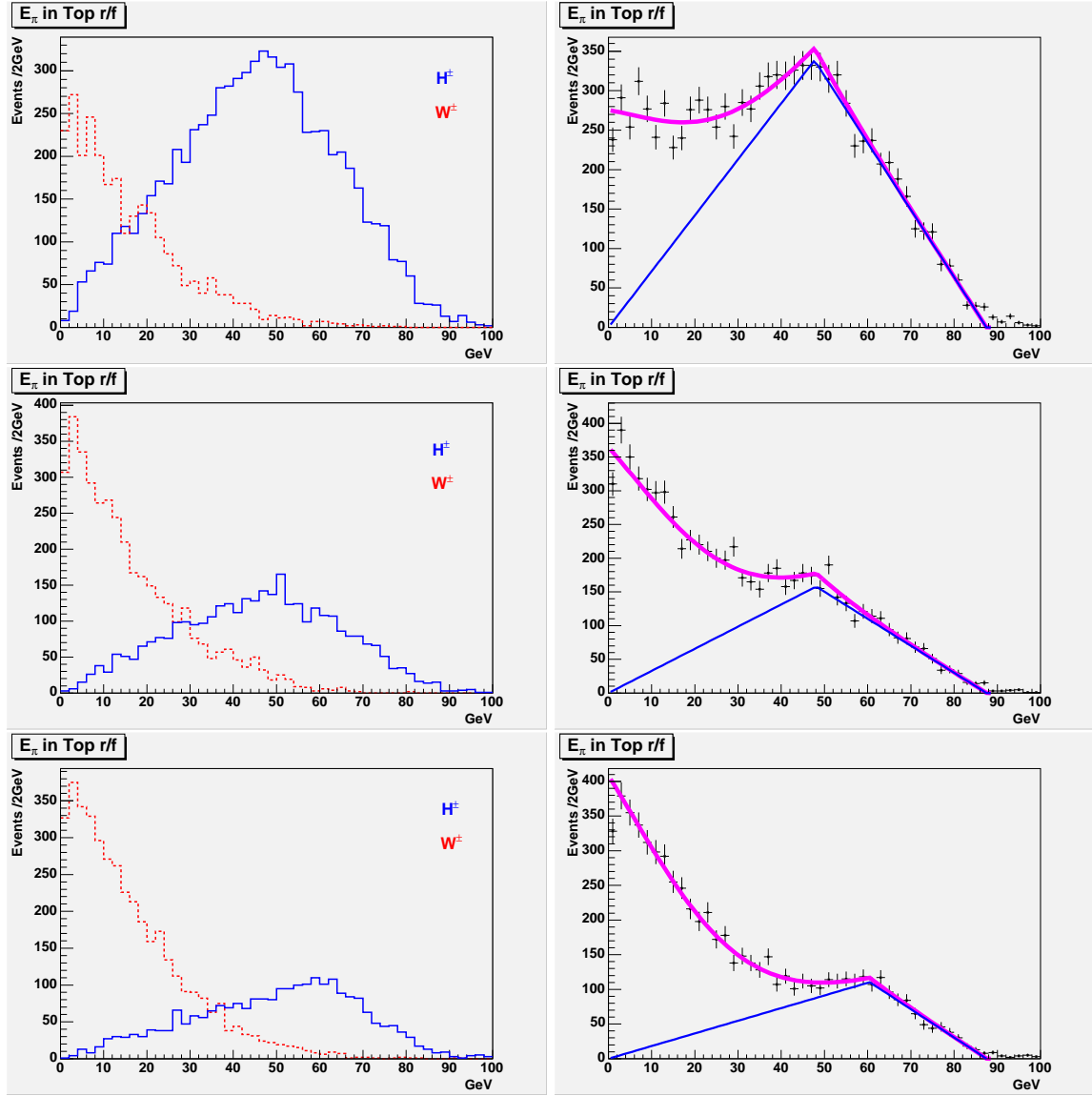
Figure 3: Generated $\pi^{\pm}$ energy spectra (left plots) and the fit (right plots) for the three sets of MSSM parameters described in the text.

energy spectrum of the pion in the $\tau^{\pm} \to \pi^{\pm}\nu$ channel allows one to infer $M_{H^{\pm}}$ with an uncertainty at the level of 0.5–1 GeV. This study is a theoretical level analysis, and no systematics or detector effects have been included. On the other hand, only one decay mode ($\tau^{\pm} \to \pi^{\pm}\nu$) has been used, and clearly if one would use other decay modes (such as the two-dimensional decay distributions of the $\tau^{\pm} \to \rho^{\pm}\nu$ and $a_1^{\pm}\nu$ decays), the sensitivity to $M_{H^{\pm}}$ would improve. Further work in this direction remains to be done.

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